

Development of Compact and High-Performance Fuel Cell Stack

Norishige Konno, Seiji Mizuno, and Hiroya Nakaji
Toyota Motor Corporation

Yuji Ishikawa
Nippon Soken Inc.

ABSTRACT

Toyota Motor Corporation (TMC) has been developing fuel cell (FC) technology since 1992, and finally “MIRAI” was launched in 15th Dec. 2014. An important step was achieved with the release of the “FCHV-adv” in 2008. It established major improvements in efficiency, driving range, durability, and cold start capability. However, enhancing performance and further reductions in size and cost are required to facilitate the commercial widespread adoption of fuel cell vehicles (FCVs). TMC met these challenges by developing the world's first FC stack without a humidifying system. This was achieved by the development of an innovative cell flow field structure and membrane electrode assembly (MEA), enabling a compact and high-performance FC stack. Other cost reduction measures incorporated by the FC stack include reducing the amount of platinum in the catalyst by two-thirds and adopting a carbon nano-coating for the separator surface treatment.

In the newly developed humidifier-less system, water management in each cell plays a key role in enhancing the performance. This requires measures to ensure proton conductivity and restrict the inhibition of gas diffusion.

The new FC stack improves the removal of water and gas diffusion by adopting a newly developed three-dimensional (3D) fine-mesh flow field at the cathode. In addition, precision stamping was adopted for the anode to create an integrated fine-pitch channel flow field with hydrogen flow on the front-side and coolant flow on the back-side. This counter-flow configuration improves the water balance inside each cell and allows humidifier-less operation by enabling self-humidification using generated water alone.

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INTRODUCTION

A fuel cell (FC) generates power by electrochemical reactions through a catalyst using hydrogen (H_2) as fuel and oxygen (O_2) in the air. Since these reactions generate only water as a by-product, FCs are regarded as an extremely clean and efficient means of generating power, with the potential to help resolve energy and environmental issues in the future.

Compared to the batteries used in electric vehicles (EV), FCs have higher power density which allows for increased vehicle on-board energy storage. As a result, FCVs have similar driving range to conventional internal combustion engine vehicles. In addition, due to FC scalability, FCs are suitable powertrain options for sedan sized passenger vehicles to large heavy duty applications such as buses for mass transportation. Toyotas vision of potential FCV markets that may emerge in the future are shown in [Figure 1](#).

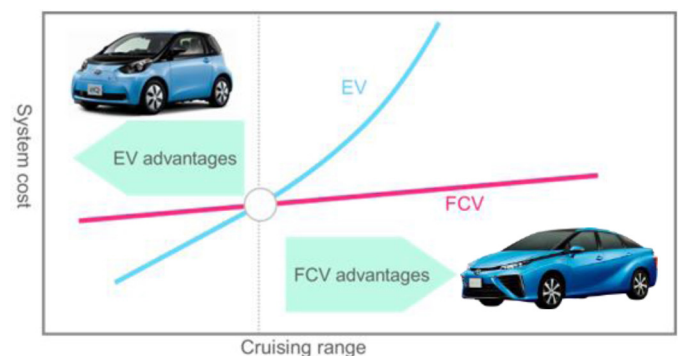


Figure 1. Vision of future mobility zones (EV and FCV)

The advantages of polymer electrolyte fuel cells (PEFCs) include the capability to start up and generate power at low temperatures, fast reaction speeds, and high current densities. As a result, FCVs tend to use this type of FC ([Fig. 2](#)).

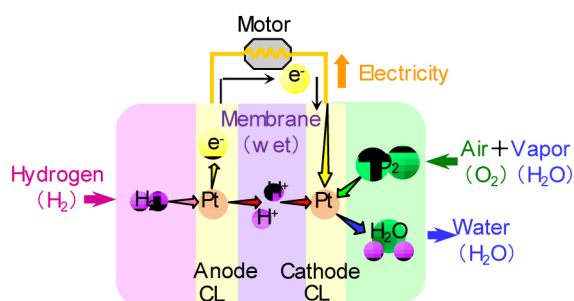


Figure 2. Generation principle of PEFCs.

To achieve the required performance with a PEFC, it is necessary to reduce the proton conductivity resistance by maintaining ionomer humidity within the electrolyte membrane and catalyst layer (CL). In a conventional FC system, FC stack humidity is managed by recirculating water from the FC stack air outlet to the FC stack air inlet through a humidifier. (Fig. 3) [1].

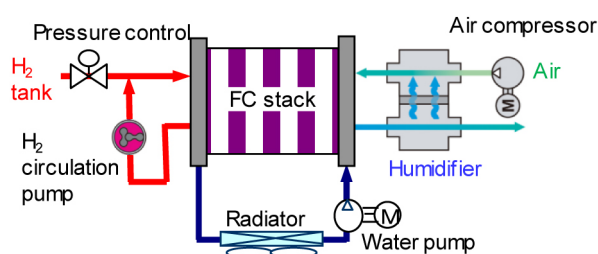


Figure 3. Conventional FC system.

ENHANCING FC STACK PERFORMANCE

Water management in each cell plays a key role in enhancing the power generation performance of the FC through ensuring sufficient diffusion of O_2 to the CL and maintaining proton conductivity. The newly developed FC stack features an innovative integrated cell flow field structure and membrane electrode & gas diffusion layer assembly (MEGA) that achieves required performance by self-humidification using generated only water.

Innovative Cell Flow Field Structure

Conventional cell flow field structures generally use straight channels. This allows a simple structure that can be manufactured using conventional stamping technology. However, when used for the cathode side flow field, this structure requires wide ribs that contact the MEGA. These ribs are susceptible to water accumulation, which adversely affects O_2 diffusion and causes non-uniform power generation [2]. In addition, although the straight channels have low pressure loss, this design is consequently susceptible to flooding by generated water. Flooding inhibits gas flows, thereby affecting gas distribution between cell layers and voltage stability (Fig. 4) [3].

The adoption of porous metal flow fields such as foamed sintered compacts that remove generated water from the MEGA by capillary force through minute holes have been studied as an alternative to straight channels. However, issues with porous metal flow fields include high pressure loss, high amounts of residual water left inside the pores, unstable product quality, and high cost [4].

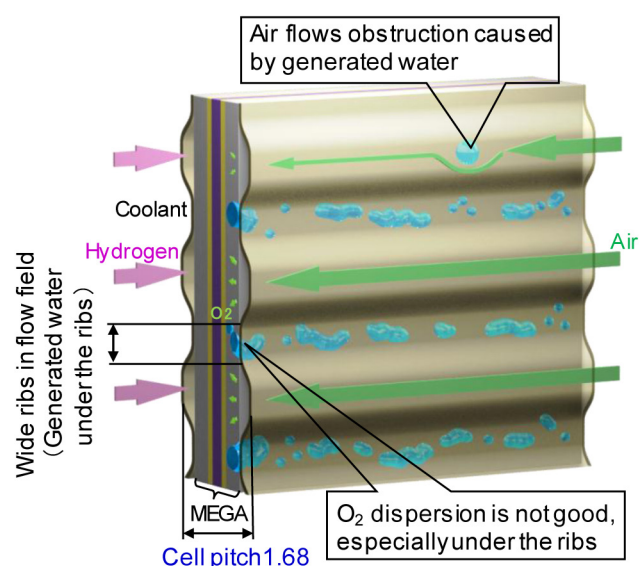


Figure 4. Conventional flow field structure.

Considering the benefits and limitations identified with traditional straight channel & porous metal flow fields, an innovative three-dimensional (3D) fine-mesh flow field was developed for the cathode. The 3D fine-mesh flow field is a 3D micro-lattice that directs air toward the MEGA and promotes O_2 diffusion to the CL. Geometry and surface wettability of the 3D fine-mesh flow field were also optimized to draw water generated by the MEGA to the back surface of the 3D fine-mesh flow field. These design characteristics help prevent mass transportation loss due to flooding, enable uniform power generation within each cell surface, and reduce voltage variations between stack cells [5]. Furthermore, the 3D fine-mesh flow field pattern within each cell surface can be modified to alleviate air inlet turbulence to help prevent drying of the MEGA. (Fig. 5 and 6)

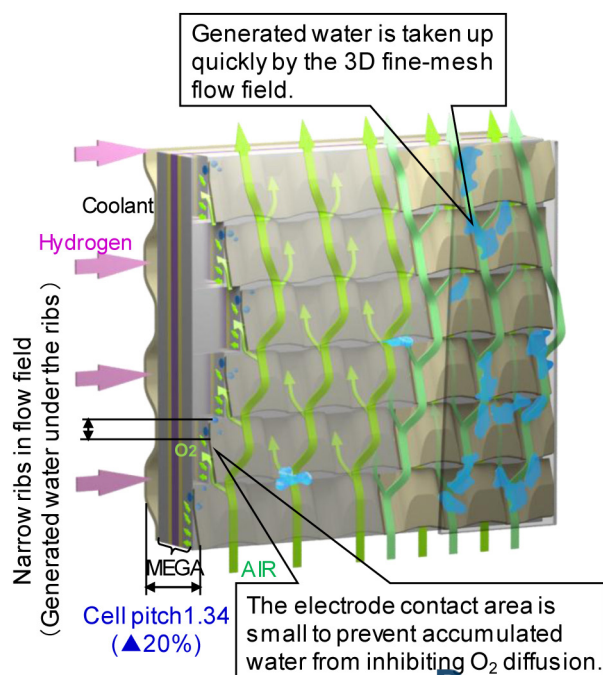


Figure 5. New 3D fine-mesh flow field structure.

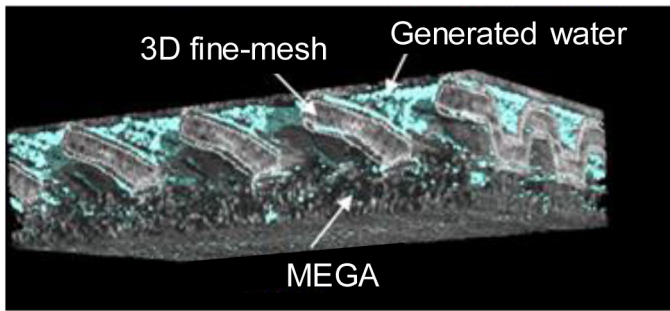


Figure 6. Location of generated water during power generation (X-ray computerized tomography (CT) image).

$$h = \left[\frac{2 * T * \cos\theta}{\rho * g * r} \right]$$

(1)

where, h is the liquid height, T is the surface tension, θ is the contact angle, ρ is the liquid density, g is the gravitational acceleration, and r is the internal diameter of the tube.

Assuming a channel was the tube, a channel width corresponds to the diameter of the tube. As h of the equation in above means that the drawing force arises in a channel, a narrow and small contact angle channel has good drainage for MEA. The narrow channel also enhances the velocity of a flowing fluid. As a result, it helps prevent from depressing of gas distribution caused by generated water flooding in channel.

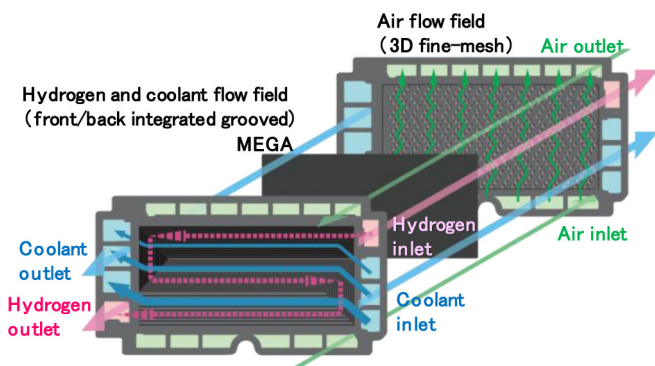


Figure 7. Directions of flow (front side: H_2 , coolant, back side: Air).

The anode utilizes an integrated channel-based fine-pitch flow field structure with H_2 flow on the front-side and coolant flow on the back-side. This creates a 2-turn, 3-step cascade microstructure in which the H_2 and air flow in counter directions on either side of the membrane electrode assembly (MEA) (Fig. 7). This structure provides several important functions to enable self-humidification. First, generated water is recycled from the air outlet through back diffusion to humidify the H_2 inlet. Second, the air inlet is humidified through back diffusion from water vapor in the anode. The H_2 pump plays a critical support role by recirculating water emitted from the H_2 outlet as vapor and transferring water generated by back diffusion from the H_2 inlet to the outlet (Fig. 8). Finally, the flow field structure is also designed to provide increased coolant flow and heat transfer

towards the air inlet by applying strategic coolant flow distribution patterns and widening flow field width. As a result, improved cathode temperature distribution was achieved which helps prevent moisture evaporation from the MEA. By applying these innovative flow field structures and water recirculation techniques, the FC stack maintains required performance at high temperatures even without a humidifier (Figs 9).

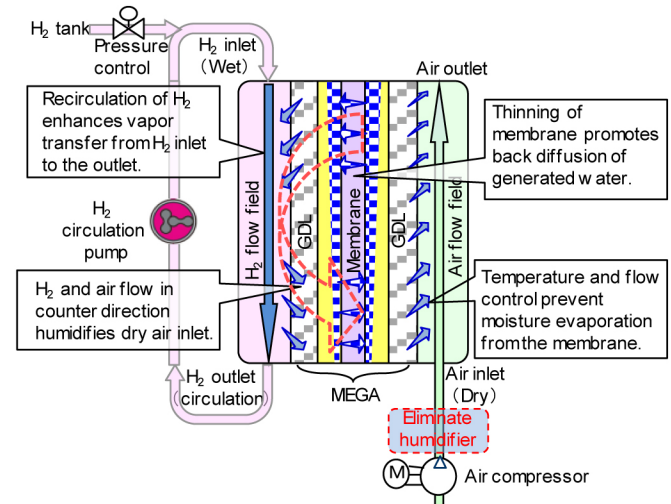


Figure 8. Outline of self-humidification within cell surface.

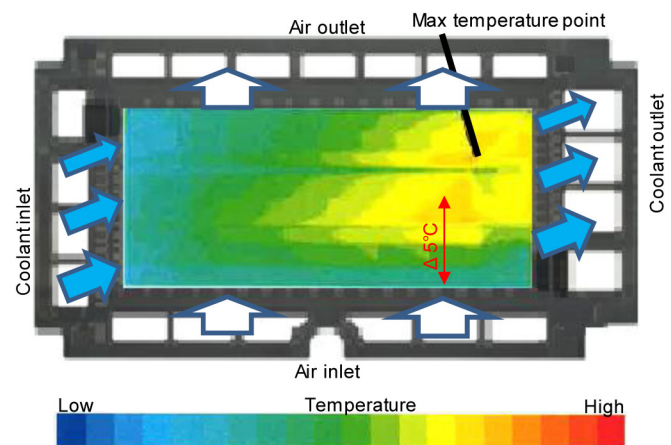


Figure 9. In-surface temperature distribution during high-temperature power generation.

Flow Field Suitable for Cold Starts in System without Humidifier

Generally, traditional FC flow field structures must be preconditioned to a dry state after shut-down to enable a successful cold start. However, as described above, a system without a humidifier must maintain water balance through generated water and back diffusion. This requires maintaining an overall higher cell water balance than a traditional humidified system during operation, and adopting measures to prevent this water from freezing and blocking the flow field during a cold start. It is particularly important to prevent blockage of the H_2 flow field since lack of H_2 can generate a reverse potential and lead to cell deterioration.